S00-224

5   Patent Application of
       Kyoungsik Yu and Olav Solgaard

                 for

Reconfigurable Wavelength Multiplexers and Filters Employing Micromirror Array in a Gires-Tournois Interferometer

The development of this invention was supported in part by contract number MDA972-00-1-0032 from the Defense Advanced Research Projects Agency (DARPA). The Government has certain rights in the invention.

RELATED APPLICATIONS

The present application claims the benefit of priority from copending provisional patent application 60/267,539, filed on Feb. 9, 2001, and which is hereby incorporated by reference.

FIELD OF THE INVENTION

The present invention relates generally to optical communications (e.g., wavelength-division multiplexing, optical code division multiple access (OCDMA), and add-drop devices). Also, the present invention is applicable to spectrophotometry, and reconfigurable optical filters.

BACKGROUND OF THE INVENTION

In the field of optical communications there is presently a need for devices that can switch different wavelengths of light. For example, in wavelength-division multiplexed communications, often it is required for individual wavelengths to be connected to different ports (e.g. fibers or

photodetectors). Also, optical add-drop multiplexers are needed to remove and then replace a single wavelength from an optical communication stream. These functions are especially difficult to implement if the device must be reconfigurable,

5   or if the wavelengths to be manipulated are very close.

Also, optical communications can benefit from reconfigurable optical filters that have a broadly controllable optical response. Reconfigurable optical filters have a number of

10 applications in the optical sciences and optical communications generally.

The present invention provides a reconfigurable optical device that can provide multiplexing, coding, spectrometer, and filtering functions.

SUMMARY OF THE INVENTION

The present invention provides an optical device having a partially reflecting, partially transmitting reflector, a movable mirror, and a light collimator. The movable mirror is spaced apart from and parallel with the reflector. The movable mirror can be moved to vary the spacing between the mirror and the reflector. The light collimator is disposed to project a light beam between the reflector and mirror at an oblique angle. An emergent beam is transmitted by the reflector each

25 time the light beam reflects from the reflector. The emergent beams are spaced apart and preferably do not overlap.

The mirror can be a single large movable mirror. In this case, the light beam reflects from the mirror multiple times; each

30 reflection is at a different position on the mirror because the light beam travels at an oblique angle.

Alternatively, the mirror can comprise an array (e.g. a linear array) of separately movable micromirrors. Each micromirror

can move vertically to vary a spacing between the micromirror and the reflector. The micromirror array can have 1-1000 micromirrors, for example. The light beam can reflect at most once from each micromirror. Alternatively, the light beam can

5   reflect 2 or 3 or more times from each micromirror.

The device can further comprise a lens for collecting the emergent beams and focusing them at a focal plane.

10 Alternatively, the mirror or micromirrors can comprise a controllable diffraction grating. The diffraction grating can vary the energy in the emergent beams.

The reflector can have a uniform or nonuniform reflectivity.
15 The reflectivity of the reflector can be graded to provide a desired energy distribution among the emergent beams.

DESCRIPTION OF THE FIGURES

Fig. **1** shows a wavelength demultiplexer according to the present invention.

20 Fig. **2** shows a plot of wavelength vs. focal plane position for the device of **Fig. 1**.

Fig. **3** shows an expanded plot of wavelength vs. focal plane position.

25 Fig. **4** shows a demultiplexer according to the present invention having a single large movable mirror.

Fig. **5** is a chart illustrating how the device of **Fig. 4** divides different wavelengths among optical fibers.

Fig. **6** illustrates how different wavelengths are distributed
30 in the focal plane in the device of **Fig. 4**.

Fig. **7** and **8** are a graph and chart illustrating the distribution of a large bandwidth input signal in a demultiplexer according to the present invention.

3

Figs. **9a** and **9b** show for different spot sizes the intensity distribution in the focal plane for different wavelengths in the device of **Fig. 4**.

Fig. **10** illustrates the intensity distribution in the focal plane for different wavelengths in the case of wavelength cycling.

Fig. **11**, **12**, **13**, and **14** are graphs for different energy distributions among the emergent beams.

Fig. **15** shows an embodiment of the present invention where each micromirror is replaced with a controllable diffraction grating.

Figs. **16** shows a closeup view of a single controllable diffraction grating in the device of **Fig. 15**.

Fig. **17** shows an alternative embodiment having a spatial light modulator for controlling the energy in the emergent beams.

Fig. **18** shows an alternative embodiment where the micromirrors have a convex shape for collimating the light beam. Fig. **19** shows an optical interleaver according to the present invention.

Figs. **20** and **21** are a graph and a chart illustrating how the device of **Fig. 19** distributes wavelengths in the focal plane.

Fig. **22** shows a reconfigurable optical filter according to the present invention.

Fig. **23a** and **23b** illustrate how the reconfigurable optical filter of **Fig. 22** can remove noise from a WDM system.

Fig. **24** shows a plot of intensity vs. focal plane position for the optical filter of **Fig 22**.

Figs. **25**, **26**, and **27** illustrate concepts in the derivation of a mathematical model of the present invention.

Fig. **28** shows a reconfigurable dispersion compensator according to the present invention.

Fig. **29** shows a reconfigurable OCDMA encoder/decoder according to the present invention.

Fig. **30** shows a spectrometer according to the present invention.

Fig. **31** shows an embodiment where the light source is disposed behind the substrate.

Fig. **32** shows an embodiment where a first reflection micromirror (the first micromirror to receive light beam **32**) is tiltable.

Fig. **33** shows an embodiment where the micromirrors are tilted so that only every second micromirror is hit by the light beam. In this embodiment, all the micromirrors, or a portion of the micromirrors can be tiltable.

Fig. **34** shows an embodiment where the reflector is not parallel with the array of micromirrors.

DETAILED DESCRIPTION

The present invention provides a reconfigurable optical device capable of filtering, multiplexing, and spectrometry, among other functions. The device has an array of micromirrors disposed under a floating reflector that is partially reflecting. The floating reflector is spaced apart from the micromirrors a certain distance, for example, 10-2500 microns. The micromirrors are each capable of independent vertical motion. In use, light is projected at an oblique angle into the space between the micromirrors and the floating reflector so that the light reflects back and forth between the floating reflector and micromirrors. Each reflection from the floating reflector produces an emergent beam from the floating reflector. Each reflection from a micromirror allows the micromirror to adjust the phase (and, in some embodiments, the amplitude) of the emergent beam. The emergent beams are combined with a lens. As a direct result of this structure, different wavelengths are focused to different points in the focal plane of the lens. Also, the focal point positions of the different wavelengths can be moved by manipulating the

micromirrors. This allows for reconfigurable filtering, spectrometry, and multiplexing, among other applications.

Fig. 1 shows a side view of an exemplary embodiment of the
5 present invention. Micromirrors **20** (individual micromirrors are labeled **20a**, **20b**, **20c**…) are disposed on a substrate **22** in a linear array. Each micromirror **20** can be independently moved in a vertical direction **24**. The micromirrors have a period spacing **A**. A floating reflector **26** is disposed above the
10 micromirrors **20** a spacing distance **T**. The spacing **T** can be used to describe the positions of individual micromirrors **20**, since they are movable. The floating reflector **26** is partially reflecting and partially transmitting and is held above the micromirror on posts (not shown) or other supporting
15 structure. A lens **28** is disposed above the floating reflector to capture emergent beams **36** transmitted by the reflector **26**. The lens **28** has a focal plane **30** where light patterns are created by the lens **28**.

20 In operation, a collimated light beam **32** from a light source **34** is projected into the space between the reflector **26** and micromirrors **20** at an angle θ (θ is typically about 2-15 degrees, and is measured from the surface normal). The light beam **32** will typically comprise several discrete wavelengths,
25 or a continuous range of wavelengths. The light beam **32** reflects back and forth between the micromirrors **20** and the reflector **26**. With each reflection from the reflector **26**, an emergent beam **36** (individual emergent beams are labeled **36a**, **36b**, **36c**…) is transmitted toward the lens **28**. The emergent
30 beams **36** are spaced apart in a horizontal direction **35**, since the light beam **32** is directed at an oblique angle. Preferably, the emergent beams **36** are not overlapping, but they can be slightly overlapping (e.g. 10% energy overlap) in the present invention. The lens **28** focuses and combines the emergent beams

36 so that a certain light pattern is formed on the focal plane 30. The light pattern produced on the focal plane depends upon the amplitudes, angles, and relative phases of the emergent beams 36. Typically, the emergent beams 36 are parallel. Relative phases of the emergent beams 36 are controlled by moving the micromirrors 20 slightly in the vertical direction 24. Phase control of each emergent beam 36 provides control over where different wavelengths are focused on the focal plane 30, and control over the shape of the focus spots in the focal plane 30.

In the specific embodiment shown in **Fig. 1**, light beam 32 comprises seven discrete wavelengths $\lambda 1$-$\lambda 7$, as commonly known in the art of wavelength division multiplexing (WDM). $\lambda 1$ is the shortest, and $\lambda 7$ is the longest wavelength, and each of the wavelengths is separated by 1nm. Each wavelength is focused to a separate point in the focal plane 30. This behavior allows the device to function as an optical multiplexer/demultiplexer. A demultiplexing function is provided by injecting the wavelengths $\lambda 1$-$\lambda 7$ in the direction shown (i.e., from light source to focal plane 30). A multiplexing function can be provided by injecting multiple wavelengths in the opposite direction, i.e. by propagating light from the focal plane 30 to the light source location.

The collimated light beam 32 has a width **W** preferably less than the size of the micromirrors 20. A light beam diameter smaller than the micromirrors 20 assures that light is not lost from the system by missing the micromirrors. For example, each micromirror can be about 150x150 microns in size, and the collimated light beam 32 can have a diameter of about 50 microns. With the micromirrors larger than the collimated beam diameter, little light will be lost if the light beam is properly aligned. The light beam 32 should remain somewhat

7

collimated as it reflected between the micromirrors and the reflector. As the light beam **32** travels, optical power can be lost if the light beam expands to become larger than the micromirrors **20**. It is noted that the micromirrors can have a

5   concave shape so that the light is refocused with each reflection. Also, the reflector can have repeating concave sections so that the light is refocused with each reflection.

The spacing distance **T** between the micromirrors and the

10   reflector **26** is essentially constant over the whole device (i.e. the micromirror **20** array and the reflector **26** can be planar parallel). Also, **T** can have a wide range of values, depending on the functionality desired. For example, **T** can be in the range of about 10-2500 microns, although larger or

15   smaller values are within the scope of the present invention. **T** is an important design parameter that influences the free spectral range (FSR) of the device, and consequently, where different wavelengths are focused in the focal plane **30**. FSR is described more fully below. Micromirrors **20** need only move

20   a fraction of a wavelength to affect the phase of the emergent beams **36**. Therefore, on a percentage basis, **T** changes only a very small amount (e.g. typically less than 1%) as the micromirrors are moved.

25   The micromirrors can be made of many materials used for micromachined structures including polysilicon, crystalline silicon, silicon nitride, SiO2, metals and the like. The micromirrors can be controlled using many different energy sources or fields, such as electrostatic fields or magnetic

30   fields. For example, the micromirrors can be vertically actuated by electrostatic vertical dual-mode comb drives.

The micromirrors can be made according to many different micromachining processes known in the art. For example, the

micromirrors can be made by surface micromachining processes such as the MUMPS® process provided by Cronos of MCNC in Research Triangle Park, North Carolina.

5   The light source **34** can be an optical fiber or waveguide carrying optical data information. The light can comprise many wavelengths multiplexed together as commonly known in wavelength division multiplexing arts. Also, the light source can also be a free space optical beam guided by bulk optical
10   components.

The light beam **32** can be collimated by any known collimator device, such as a lens, hologram, curved mirror or the like. The light beam **32** can be collimated by a cylindrical lens that
15   focuses the light in one dimension, or by a conventional lens that focuses light in two dimensions.

The micromirror period spacing A can be slightly larger than the micromirrors, so that the micromirrors are separated by small gaps. For example, the micromirrors can be in the range
20   of about 50-200 microns square, and separated by 5-25 micron gaps, so that the mirror period spacing is in the range of about 55-225 microns. Larger or small values for micromirror size and period spacing are also contemplated by the inventors
25   and are within the scope of the present invention.

The number of micromirrors **20** in the array, N, can be in the range of about 1-1000, although larger numbers of micromirrors **20** are within the scope of the present invention. The device
30   of **Fig. 1** has 7 micromirrors. The number of micromirrors **20** generally depends upon the resolution desired for separating wavelengths. With all other factors being equal, a larger number of micromirrors provides greater wavelength resolving power. It is noted that the present invention includes an

embodiment having a single movable mirror to vary the gap spacing T; in this embodiment, the light beam **32** can reflect from the single mirror multiple times.

5   The number of emergent beams **36** in the array is typically equal to the number of micromirrors N, or N+1 (if the light beam **32** is incident on the reflector **26** as shown in **Fig. 1**), but not necessarily so. The number of emergent beams **36** can be greater than the number of micromirrors if the light beam **32**

10 reflects from each micromirror multiple times. The number of emergent beams **36** in the present invention must be at least 2, and can be 1000 or more. In the present description, the number of emergent beams **36** is given by the variable M.

15 The lens **28** can be a lens assembly comprising multiple lenses for diffraction-limited focusing. The lens can also be a holographic element or any other device providing a focusing function.

20 The substrate can be any substrate used for fabricating microoptical, or microelectromechanical (MEM) devices. The substrate can be made of silicon, which is commonly used for micromechanical devices, or can be made of other materials such as ceramic, glass, or metal.

25

The reflector **26** can be made of a dielectric, semiconductor or metallic thin films (e.g. silicon nitride, SiO2, silicon, aluminum) or combination of materials (e.g. multiple layers). The reflector can be a free standing thin film or a second

30 substrate having substantial thickness.

Application in Multiplexing/Demultiplexing

In the present invention, the free spectral range (FSR) of the device is very important for characterizing the device behavior. In the present invention, the FSR is approximately:

$$FSR \cong \frac{\lambda^2}{2T\cos\theta}$$

5

where λ is approximately the wavelengths used in the device (e.g. if a range of 1530-1580 nm is used, λ in the above equation can be about 1550 nm), T is the micromirror-reflector spacing, and θ is the incidence angle. In the present invention, the FSR is the wavelength range that can be resolved in the focal plane without multiple wavelengths being focused to the same position in the focal plane (i.e. overlapping); this is more fully explained below.

15

In the present invention, wavelengths are distributed in the focal plane so that there is a well-defined correspondence between wavelength and position in the focal plane. **Fig. 2**, for example, shows a plot of wavelength versus focal plane position (in the instance where all micromirrors have the same value of T). Wavelength varies approximately linearly with linear position in the focal plane. A larger view of the wavelength vs. focal plane position in **Fig. 3** reveals that the wavelength pattern repeats in the focal plane. Each repeating unit is called a 'window' in the present description (typically, a window can be about 0.5-3mm wide, for example)_ The wavelength range in each repeating 'window' is equal to the FSR of the device. Each window corresponds to a different diffraction order. Typically (and desirably), most of the optical energy is located in a single window, but the invention is not so limited. In the example of **Figs 2** and **3**, the FSR is equal to the wavelength range $\lambda1-\lambda7$, or 7 nm.

Fig. 4 shows an alternative embodiment of the invention where the micromirrors **20** are replaced with a single movable mirror **42**. In this embodiment, movement of the mirror **42** can shift the wavelengths in the focal plane. The device of **Fig. 4** is shown being used as a demultiplexer, although application as a multiplexer is also possible. Here, microlenses **39** (optional) are used to focus the wavelengths $\lambda 1$-$\lambda 7$ into seven optical fibers **40** (microlenses and optical fibers may be referred to herein as output ports). The lenses **39** and fibers **40** are located at or near the focal plane **30**. The optical fibers **40** are numbered 1-7 as shown. In this example, $\lambda 1$-$\lambda 7$ can be wavelengths separated by 1 nm and centered around 1550nm. In the present specification, $\delta\lambda$ indicates wavelength spacing between adjacent channels (1 nm in example above), and $\Delta\lambda$ indicates a total input wavelength range of input light (7 nm in example above).

In the present reconfigurable optical demultiplexer, the wavelengths $\lambda 1$-$\lambda 7$ can be switched between the optical fibers 1-7 by moving the mirror **42** in the vertical direction **24**. With the specific micromirror setting of **Fig. 4**, optical fiber **1** receives $\lambda 1$, optical fiber **2** receives $\lambda 2$, and so on.

Fig. 5 shows a chart illustrating which fibers **40** receive which wavelengths for certain positions of mirror **42** in the device of **Fig. 4**. Each column corresponds to a different mirror position. Column 1 of **Fig. 5** for example corresponds to the wavelength pattern shown in **Fig. 4**. From **Fig. 7** it is apparent that the wavelengths $\lambda 1$-$\lambda 7$ 'cycle' through all the optical fiber ports as spacing T is varied. A wavelength that cycles past optical fiber **7** reappears at optical fiber **1**. If the mirror is moved a relatively large distance, eventually the pattern repeats, as illustrated by column **8**, which is the same as column 1.

It is important to note that mirror **42** moves a very small amount to cause the wavelengths to shift. The required vertical displacement is a small fraction of the wavelength used (e.g. 1/10 to $1/2\lambda$ for example). 1530-1580nm may be a typical wavelength range used, and T may be about 50-400 microns, so T is not significantly changed by mirror displacements required for wavelength shifting. Therefore, the FSR is not significantly changed as wavelengths are shifted between optical fibers **40**.

Fig. 6 shows another illustration of wavelength cycling in the zero order window only. In **Fig. 6**, the wavelengths have been shifted about halfway across the window.

In many multiplexing and demultiplexing applications of the present invention, it is desirable for the total range of input wavelengths to be less than or equal to the FSR. If this condition is satisfied, then no two wavelengths will be focused to the same position in the focal plane. If the range of input wavelengths is greater than the FSR, then multiple wavelengths will be focused at the same positions. For example, **Fig. 7** illustrates a situation where wavelengths $\lambda1$-$\lambda14$ are input into the device of **Fig. 4**. Wavelengths $\lambda8$-$\lambda14$ have the same $\delta\lambda$ $\lambda1$-$\lambda7$ (1 nm); so wavelengths $\lambda1$-$\lambda14$ have a bandwidth $\Delta\lambda$ (14nm) twice the FSR (7nm). In this case, $\lambda1$ and $\lambda8$ will be focused to the same position in the focal plane; $\lambda2$ and $\lambda9$ will be focused to the same position; $\lambda3$ and $\lambda10$ will be focused to the same position, and so on. **Fig. 8** shows a chart illustrating wavelength cycling in the same manner as the chart of **Fig. 5** (each column corresponds to a different vertical position for mirror **42**). Wavelengths $\lambda8$-$\lambda14$ cycle in the same manner as wavelengths $\lambda1$-$\lambda7$.

Another important design consideration of the present device is the wavelength resolution, which influences crosstalk when the device is used as a demultiplexer. Each wavelength is focused to a spot having a finite spot size. The spot size, and crosstalk are related to the wavelength resolution of the device, which is defined as:

$$\text{Resolution} = \frac{1}{\Lambda} = \frac{M}{FSR}$$

where Λ is the minimum wavelength difference between two separable wavelengths, M is the number of emergent beams **36**, and FSR is the free spectral range defined above. The above equation assumes the emergent beams **36** have equal energy. Unequal energy distribution among the emergent beams will often, but not always, provide somewhat lower wavelength resolution.

High resolution is desirable for dense wavelength division multiplexing devices and many other applications. **Fig. 9a** and **9b** illustrate exemplary light distributions in the focal plane **30** for high resolution and low resolution devices, respectively. The wavelength pattern of **Fig. 9a** can be changed to resemble the wavelength pattern of **Fig. 9b** by reducing the number of emergent beams **36** (e.g. by blocking some of the emergent beams **36**), or by increasing the FSR, for example.

Fig. 10 is a plot of the wavelength pattern in the focal plane, further illustrating wavelength cycling, where the wavelengths $\lambda 1 - \lambda 7$ have been shifted by two steps.

In the present invention, the reflector **26** can have a uniform reflectivity or graded (nonuniform) reflectivity. The reflectivity of the reflector strongly influences the

amplitude of the emergent beams **36**, which effects the device resolution.

Fig. 11 shows a plot of emergent beam energy versus beam
5 number for a device with the reflector **26** having uniform reflectivity. The energies of the emergent beams **36** is exponentially decreasing. Exponential beam energy distribution tends to result in a relatively low resolution.

10 **Fig. 12** shows a plot of beam energy and reflector reflectivity versus beam number for a device with a linearly graded reflectivity. Beams close to the middle (e.g. emergent beam **36d**) tend to have the highest beam energy. This energy distribution tends to result in an improved wavelength
15 resolution compared to the distribution of **Fig. 11**.

Fig. 13 shows a plot of beam energy versus beam number for a device with a uniform energy distribution among the beams **36**. A uniform beam energy distribution tends to provide tightly
20 focused spots for each wavelength. A uniform beam energy distribution can be provided by appropriately grading the reflector reflectivity, or by other techniques discussed below.

25 **Fig. 14** shows a plot of beam energy versus beam number for a device with an energy distribution varying according to a sinc function (sinx/x). A sinc function energy distribution tends to focus each wavelength to a box-like area since the Fourier transform of a box is a sinc distribution. Focusing each
30 wavelength to a box-like area tends to provide lower crosstalk between adjacent channels. A sinc function beam energy distribution can be provided by appropriately grading the reflector reflectivity, or by other techniques discussed below.

The amplitudes of the emergent beams **36** can be controlled, for example, by fabricating the micromirrors **20** with different reflectivities, or by fabricating a single large mirror **42** with a graded (nonuniform) reflectivity. Alternatively, a spatial light modulator such as an array of liquid crystal light valves can be placed above the reflector **26**. Each light valve can control the energy in an emergent beam **36**.

It is noted that the reflector **26** can have a reflectivity graded in various ways. For example, the reflector can have a Gaussian graded reflectivity (i.e. the reflectivity varies as a Gaussian function with position), an exponential graded reflectivity, or a triangular graded reflectivity, for example. Many other graded reflectivities are possible.

Fig. 15 shows a perspective view of an alternative embodiment of the present invention where each micromirror is capable of independently modulating its reflectivity. This allows independent control of the amplitude of each emergent beam **36**. In the device of **Fig. 15**, each micromirror **20a, 20b, 20c, 20d** comprises separately movable mirror diffractive elements **43** (typically at least 4 elements per micromirror). Reflector **26** is a narrow strip aligned over the micromirrors **20**. The lens **28** and focal plane are not shown in **Fig. 15**. The separately movable mirror elements **43** act as a diffraction grating when they are positioned at different heights. In operation, light beam **32** reflects between the reflector **26** and micromirrors **20** when the mirror elements **43** are coplanar. When elements **43** are positioned at different heights (e.g. like micromirror **20b**), light beam **32** is partially diffracted. The diffracted light misses the reflector **26** and becomes the emergent beam **36**, which is collected by lens **28** (not shown). The undiffracted portion of light beam **32** continues to reflect between the

reflector **26** and micromirrors **20**. By adjusting the positions of the elements **43**, the amount of energy in the emergent beam **36** can be controlled. Specifically, the less coplanar the elements **43**, the more energy is present in the corresponding emergent beam **36**. If all the micromirrors in the device comprise elements **43**, the energy of each emergent beam **36** in the present invention can be independently controlled. For more information on controllable diffraction gratings, and movable mirror elements, reference can be made US patents 5,459,610 and 5,808,797 to Bloom et al.

It is noted that the diffractive elements **43** can move in unison so that the elements **43** act as a single micromirror . In this way, the elements **43** can provide phase tunability without affecting the energy of the emergent beams **36**. So, when a micromirror comprises diffractive elements **43**, the diffractive elements can be actuated to provide independent control over energy and phase of the corresponding emergent beam **36**.

Fig. 16 shows a closeup perspective view of a single micromirror **20** comprising diffractive elements **43**. Reflector is shown as a layer of material with a highly reflective region **26a** and a highly transmissive region **26b**. The reflective region **26a** is disposed to reflect undiffracted light beam **32**; the transmissive region is disposed to transmit diffracted light that forms emergent beam **36**. The device of **Fig. 16** is not shown to scale; typically, the reflective region **26a** will be as wide or wider than the micromirror **20**.

Fig. 17 shows another embodiment of the present invention where the energy in each emergent beam can be independently controlled. Here, a spatial light modulator **45** (SLM) is disposed above the reflector **26**. The SLM comprises an array of light valves (e.g. liquid crystal light valves), with each

emergent beam **36** passing through a separate light valve. Controlling the opacity or reflectivity of the light valves controls the energy in the corresponding emergent beam **36**. Optionally, the SLM **45** and reflector **26** can be combined in a single device where each light valve of the SLM has a variable reflectivity. In this way, the energy of each emergent beam **36** can be controlled without loss of optical energy from the system. By contrast, an SLM with variable opacity will tend to absorb substantial amounts of optical energy, which is undesirable. A device that can function as a variable reflectivity SLM is described in "MEMS-based variable optical interference devices" by Goossen, K.W. Optical MEMS, 2000 IEEE/LEOS International Conference, Pages 17-18. Other SLM devices with variable reflectivity can be made using MEMS technology.

Fig. 18 shows an alternative embodiment where the micromirrors **20** have a convex shape focusing the light beam **32**. Although every micromirror **20** is shown having a convex shape, it is also possible to make a device with both flat and convex micromirrors. For example, every second or third micromirror **20** can have a convex shape, and other micromirrors can be flat. In operation, the convex shape of the micromirrors **20** causes the light beam **32** to be repeatedly refocused. Alternatively, the reflector **26** can have convex bumps for refocusing the light beam **32**. It is noted that the mirror **42** of **Fig. 4** can have an array of convex shapes for focusing the light beam **32**.

Application in Optical Interleaving

The present invention can function as an optical interleaver in which alternate wavelengths (e.g. 20 discrete wavelengths) are divided among 2, 3, 4 or more output ports. For example,

wavelengths $\lambda 1$-$\lambda 14$ (with $\delta\lambda$ of 1 nm) can be divided between two output ports so that 7 wavelengths go to each port

5   In order to function as an optical interleaver, the device must have an FSR smaller than the range of input wavelengths $\Delta\lambda$.

Fig. 19 shows a device configured to function as an optical interleaver. All the input wavelengths are focused to two spots **52**, **54**, where port 1 and port 2 are located, respectively. In this example, wavelengths $\lambda 1$- $\lambda 6$ are in beam **32**. Each wavelength $\lambda 1$- $\lambda 6$ has $\delta\lambda$ of 1 nm for a total bandwidth $\Delta\lambda$ of 6nm. The FSR is 2 nm. Wavelengths $\lambda 1$, $\lambda 3$, and $\lambda 5$ are focused into port 1; Wavelengths $\lambda 2$, $\lambda 4$, and $\lambda 6$ are focused into port 2. Port 1 and port 2 can be optical fibers, photodetectors or any other device for receiving light.

Fig. 20 shows a plot of wavelength versus focal plane position for the device of **Fig. 19**. The wavelengths $\lambda 1$-$\lambda 6$ span 3 FSRs. **Fig. 21** shows a chart illustrating that the wavelengths can be switched between ports by adjusting mirror position. All the mirrors can move up and down together so they are coplanar in all positions.

25 More generally, the number of ports in to which wavelength channels are separated is equal to

$$\# \text{of ports} = \frac{\text{FSR}}{\delta\lambda},$$

30 where $\delta\lambda$ is the wavelength difference between adjacent channels (assuming all channels have the same wavelength separation). For example, if $\delta\lambda$ is 3nm, and the FSR is 12nm, then the wavelengths will be separated into 4 ports. If 8 wavelengths are present, each port will receive 2 wavelengths. If 4

wavelengths are present, then each port will receive a single wavelength and the device will function as a multiplexer or demultiplexer as described above. Mirror motion cycles the wavelengths among the ports, but the same wavelengths are always found together.

It is noted that the optical interleaver according to the present invention can have a single large mirror **42** instead of a micromirror array. In fact, an optical interleaver can be very similar to the device of **Fig. 4**, with the exception that an interleaver will have a smaller FSR compared to the input bandwidth $\Delta\lambda$.

Application in Reconfigurable Optical Filtering

The present invention can be used as a reconfigurable optical filter with a periodic response. Such a filter can be used in wavelength division multiplexing to provide multiple passbands with each passband centered on a wavelength channel. In this application, the FSR is equal to $\delta\lambda$, and all the wavelength channels are focused to the same output port. Such a device is useful for removing unwanted noise between wavelength channels, or for narrowing channel spectral width. Wavelengths between channels are focused to positions outside the output port.

Fig. 22 shows a reconfigurable optical filter according to the present invention. All the wavelengths of interest (channel wavelengths $\lambda 1$-$\lambda 6$) are focused to a single output port **56**. In this example, $\delta\lambda$ is 1 nm, and the FSR is 1 nm.

Fig. 23a shows a plot of input energy versus wavelength for input beam **32** of **Fig. 22**. In WDM applications, the input beam typically has unwanted noise **55** between channel wavelengths. **Fig. 23b** shows a plot of passbands **57** and output energy versus

wavelength. Passbands have a spectral width **58** (necessarily less than the FSR), and typically all the passbands have the same spectral width. The passbands **57** are separated by 1 FSR since there is only one output port **56**. Although the passbands are shown having a box shape, they can have many different shapes, such as a Gaussian shape as illustrated by passband **59**. Typically, all the passbands in a filter device will have the same shape. In the example of **Figs 23a-23b**, noise between the wavelength channels is removed from the system by being focused in an area of the focal plane away from the output port **56**. This results in a reduction in the background noise level, which is seen in the bottom graph of **Fig. 23b**.

Fig. 24 shows a plot of intensity versus position in the focal plane, further illustrating the behavior of the device of **Fig. 22**. Solid line **60** represents the intensity distribution of all the wavelengths within the passbands **57**. Wavelengths $\lambda 1$, $\lambda 2$, $\lambda 3$, $\lambda 4$, $\lambda 5$, and $\lambda 6$ all have intensity distributions given by solid line **60** Dotted line **62** represents the intensity distribution of all the wavelengths outside the passbands **57**. Output port **56** of **Fig. 22** receives all the light within area represented by range **64**.

The spectral width of the passbands can be changed by changing the port range **64**, by positioning the micromirrors **20** to affect the shape of the solid line **60** (which is accomplished by moving micromirrors **20**), or by changing the spot size. Spot size can be altered by changing the number of emergent beams **36**, or by changing the energy distribution among the emergent beams **36**, as described in reference to **Figs. 9a** and **9b**. Spot size can also be changed by changing the focal length of the lens **28**.

In the reconfigurable filter, the passband width is determined by the port range, window width, and the FSR approximately according to the following equation

$$\text{Passband width} = \frac{P_r}{G} FSR$$

5

where P_r is the port range, G is the window width, and FSR is the free spectral range.

According to the present invention, the shape of the spatial energy distribution (e.g. solid line **60** in **Fig. 24**) is a function of the vertical positions of the micromirrors **20**. A Technique for calculating micromirror positions from desired energy distribution shapes is described below in the 'Theory and Algorithms' section. The filter of the present invention is reconfigurable because the shape of the energy distribution **60**, and hence the passband widths, is adjustable. Also, FSR is adjustable by changing T.

The multiplexer, interleaver, and filter of the present invention operate according to similar theory (described below), but operate in different regimes. The multiplexer has a FSR equal to or larger than input wavelength range $\Delta\lambda$, the filter has a FSR smaller than input wavelength range $\Delta\lambda$. In the multiplexer, the ratio FSR/$\delta\lambda$ gives the number of ports. In the filter and in the interleaver, the ratio $\Delta\lambda$/FSR gives approximately the number of wavelengths that are present at each output port.

It is noted that the optical filter according to the present invention can have a single large mirror **42** instead of a micromirror array. In fact, an optical filter can be very similar to the device of **Fig. 4**, with the exception that a filter will typically have a much smaller FSR than a demultiplexer/multiplexer.

Theory and Algorithms

For convenience, we repeat here important design parameters of the present invention.

Name	Description	Typical value
T	separation length between mirror-array and reflecting film	10μm ~ 2.5mm
w	Beam width of incident light	20 ~ 75 μm
λ	Light wavelength	800nm or 1.55μm
N	Total number of micromirrors	1 ~ 1000
A	Mirror period	50 ~ 200 μm
θ	Incident angle of incident beam	2 ~ 15°

If one micromirror is moved vertically, the optical path length changes to give a phase-shift to the corresponding emergent beam. In addition to this phase-shift induced by the mirror movement, there is an intrinsic phase-shift due to the free-propagation of light between micromirrors **20** and reflector **26**. This phase shift occurs even when there is no micromirror movement. In the case where the micromirrors are not displaced, the optical path length difference between two adjacent emergent beams is

$$\text{Path length difference} = \Delta = 2T\cos\theta,$$

the optical phase difference between two adjacent emergent beams is $\Delta\dfrac{2\pi}{\lambda}$ radians for wavelength λ.

The nominal optical path length difference δ, measured when there is no micromirror displacement, is in this example the same for all adjacent emergent beams. δ is a constant, once the

23

☒

incident angle θ and separation length T are determined. The corresponding phase difference is $\delta = \frac{2\pi}{\lambda}\Delta$. By taking the phase of the first emerging beam as a reference, the relative phase of nth beam is $(n-1)\delta$ or, equivalently, $\sum_{2}^{n}\frac{2\pi}{\lambda}\Delta$ when there is no

5   mirror movement (summation starting at 2 implies that the light beam reflects from the reflector **26** before the first micromirror). If we move the micromirrors, an additional phase will be added (or subtracted) to this free space propagation phase.

10

If displacement of the nth mirror from its original position is denoted as $h(n)$, the additional amount of phase shift made by mirror repositioning is equal to $\phi(n) = \frac{2\pi}{\lambda}(2h(n)\cos\theta)$. **Fig. 25** shows a diagram of a micromirror at two different vertical

15   positions illustrating how this equation is derived.

The important thing to remember here is that all emergent beams are tapped from a single light beam 32, and the effect of micromirror reposition propagates to all the emergent beams

20   downstream. In other words, the phase term of nth beam should be equal to $\sum_{k=2}^{n}(\delta + \phi(k))$. From this expression, it follows that the phasor representation of nth beam can be written as $E_{n}e^{j\psi(n)}e^{j\delta(n-1)}$, where $\psi(n)$ is the effective phase shift of the nth beam accumulated from the phase shifts from upstream

25   micromirror reflections. That is, $\psi(n) = \sum_{k=2}^{n}\phi(k)$.

The amplitude is controlled by the reflection coefficient of the thin film (typically fixed, but the invention is not so limited), and the phase is controlled by micromirror vertical position, i.e. we can change the phase but not the amplitude of the emergent beams in this implementation.

5

As described above, the micromirror period **A** (equal to 2Ttanθ), should be greater than beam width w so that adjacent emergent beams are not overlapping. **Fig. 26** illustrates this arrangement. If the emergent beams are not overlapping, the emergent beams can be modeled in the far field as a multiple-slit diffraction problem, which is well-understood in the field of optics. The 'slit width', b, is given by $b = \dfrac{w}{\cos\theta}$, where w is the beam width; for small θ, b≅w. The separation distance between the beams is a=2Ttanθ.

10

15

Assuming the device can be modeled as a multiple-slit system, and Fraunhofer approximation, the electric field (far field) E measured at angle σ and distance R after focusing (or transforming) lens can be written as:

20

$$E(R,\sigma,t) = \mathrm{Im}\left[(bCe^{j(wt-kR)})(\frac{\sin\beta}{\beta})(\sum_{n=0}^{N-1} E_{n+1}e^{j\psi(n+1)}e^{j\alpha n}) \right] \quad \text{Eq. 1}$$

where:

α=δ+0.5kasinσ

$\beta = 0.5kbsin\sigma$

$k = \dfrac{2\pi}{\lambda}$, ω is angular velocity, t is time, and C is a constant.

Significantly, it is noted that the last term of Eq. 1 $\sum_{n=0}^{N-1} E_{n+1} e^{j\psi(n+1)} e^{j\omega n}$ has a form of a discrete-time Fourier transform.

5   For more information on discrete-time Fourier transforms, and their application to digital signal processing, reference can be made to the following publications: "Discrete-Time Signal Processing" by Oppenheim et al. and published by Prentice Hall, 1999, and "Optical Filter Design and Analysis: A Signal

10   Processing Approach" by Christie K. Madsen, Jian H. Zhao, Christi K. Madsen, Wiley Series in Microwave and Optical Engineering. In the present invention, there is an analogy between combining the emergent beams, and the behavior of a transversal filter (TF). A transversal filter combines

15   multiple identical signals having different amplitudes and phase delays. More specifically, the time delay between each tap in a TF is proportional to spacing T in the present invention. The impulse response in a TF is analogous to the set of emergent beams expressed as complex numbers.

20   Theoretical understanding of transversal filters is well known in the art.

Since the far field pattern in the focal plane is given by a discrete time Fourier transform, wavelengths are focused to different points in the focal plane, and wavelengths can be

25   moved (cycled) in the focal plane by phase adjustments to the emergent beams.

In the present invention, a certain intensity distribution in the focal plane may be desired. This is particularly true in the reconfigurable filter application, where intensity

distribution in the focal plane influences the passband widths. In many applications of the present invention, it is desirable to adjust the mirror heights so that each wavelength has a certain intensity distribution (i.e. spot shape).

A technique for determining micromirror heights from a desired intensity distribution can be summarized in 4 steps:

1) Select upper and lower bounds on far field pattern in the focal plane.

2) Select number of emergent beams (typically N or N+1).

3) Express each emergent beam as a single complex number. Each complex number includes amplitude and phase information. It is assumed that all emergent beams are parallel.

4) Find values for the complex numbers so that a transform (e.g. Fourier transform, discrete-time Fourier transform, Z-transform, or Laplace transform) of the series of complex numbers satisfies the upper and lower bounds selected in step (1). If desired, adjustments can be restricted to phase adjustments (optionally, adjustments can include both amplitude and phase adjustments). Techniques for performing this calculation are known in the art and are identified below. The transform is selected to describe the transfer function of the focusing device (i.e., lens **28**).

This technique assumes that all the emergent beams have the same angle θ.

Fig. 27 shows a diagram of upper bound B_u and lower bound B_l for the far-field pattern for a single wavelength. In the multiplexer/demultiplexer device of the present invention, each wavelength will have approximately the same upper and lower bound shape, although for different wavelengths the bounds will be in different locations in the focal plane. In

the filter application, the upper and lower bounds will have the same shape and be in the same location for all wavelengths in the passbands.

5   In the present invention, micromirror positions are determined so that each wavelength or set of wavelengths satisfies the corresponding upper bound $B_u(x)$ and lower bound $B_1(x)$, where x indicates position in the focal plane. The upper and lower bounds are functions of the focal plane position x. In order to find the micromirror positions that satisfy the upper bound $B_u(x)$ and lower bound $B_1(x)$, the emergent beams are expressed as a series of complex numbers $(u_1, u_2, u_3, ...u_N)$. Each complex number includes amplitude and phase information:

$$U=(u_1, u_2, u_3, ...u_N).$$

Then, we must find values of $(u_1, u_2, u_3, ...u_N)$ that satisfy the following equation:

$$B_1(x) < |F\{U\}| < B_u(x),$$

Where 'F' represents a discrete-time Fourier transform or other transform function (e.g. Laplace transform, Z-transform) that describes the focusing device. $F\{U\}$ is understood to be a 25 function of x (position in the focal plane) since the present invention maps wavelength into position in the focal plane. $F\{U\}$ is in general a complex number, so it is usually necessary to compare absolute values as shown. There are two possible cases: (1) adjustment of both amplitude and phase of 30 the emergent beams to satisfy B_u and B_1, or (2) adjustment of phase only to satisfy B_u and B_1. Each case is more fully explained below.

Case (1): Adjustment of amplitude and phase

In this case, the problem is well analyzed in digital signal processing literature. Specifically, the problem is solved in transversal filter. For more information, reference can be made to "Discrete-Time Signal Processing" by Oppenheim et al. In the present invention, phase is adjusted by vertical positioning of the micromirrors, and amplitude can be adjusted by reconfigurable diffraction gratings (as described with reference to **Figs. 15-16**), or spatial light modulators.

Case (2): Adjustment of phase only

In this case, only the phases is adjusted, and the problem can be restated as:

Find $(u_1, u_2, u_3, ...u_N)$ for $B_1(x) < |F\{U\}| < B_u(x)$, where $|u_1|$, $|u_2|$, $|u_3|,... |u_N|$ are given.

Techniques for solving this problem are known in the art. For example, Bucci et al. describe a technique for solving this problem in "Intersection Approach to Array Pattern Synthesis", IEEE Proc., pt. H, vol. 137, no. 6, pp. 349-357, Dec, 1991, which is hereby incorporated by reference.

It is noted that, if certain bounds B_u, B_1 require micromirrors to be nonplanar (i.e. micromirrors have different heights and associated values of T), then wavelength cycling is provided by moving all the micromirrors the same amount, so that relative vertical positions of the micromirrors remain constant.

It is noted in the filter embodiment, micromirror positions for a certain passband shape can be determined by appropriately shaping the upper bound and lower bound. The

passbands can have many different shapes by properly positioning the micromirrors.

Alternative Embodiments

5   **Fig. 28** shows an embodiment of the present invention functioning as a dispersion compensator. A mirror **70** is disposed at the focal plane **30**. Light from the lens **28** is focused on the mirror **70**, which reflects the light back into the lens **28**. The light then returns along the input beam **32**, 10 or close to the input beam **32**. The dispersion in the present device can be adjusted by moving the wavelengths in the focal plane, which is accomplished by moving the micromirrors **20**, or in another embodiment, by moving the single large mirror **42**. Dispersion compensation is described in "Chromatic Dispersion 15 Compensator using Virtually Imaged Phased Array" by M. Shirasaki in IEEE Photonics Technology Letters, vol. 9, no. 12, pp. 1598-1600, Dec. 1997, which is hereby incorporated by reference.

20 **Fig. 29** shows an embodiment of the present invention used as an optical code-division multiple access (OCDMA) encoder. Optical fibers **73**, **75**, **77**, **79** of different lengths are disposed at the focal plane to receive different wavelengths. The optical fibers **73**, **75**, **77**, **79** provide different time 25 delays to the different wavelengths. The device shown in Fig. 19 can provide temporal/wavelength two-dimensional codes for incoherent OCDMA systems. Two-dimensional codes can outperform single dimension wavelength OCDMA codes. Specifically, two dimensional codes can have a higher number of users for a 30 given bit-error rate. For more information on two-dimensional temporal/wavelength coding techniques, reference can be made to "Wavelength-Time Spreading Optical CDMA System using Wavelength Multiplexers and Mirrored Fiber Delay Lines" by Yu et al. in IEEE Photonics Technology Letters, vol. 12, no. 9,

2000, which is hereby incorporated by reference. The device of **Fig. 29** can also function as a decoder, if light travels in a direction from the optical fibers to the light source.

5   **Fig. 30** shows a spectrometer according to the present invention. In this embodiment, a photodetector array **80** is disposed at the focal plane. Different photodetectors in the photodetector array will receive different wavelengths.

10 **Fig. 31** shows an embodiment of the invention where the light source **34** is disposed behind the substrate **22**. In this embodiment, the number of emergent beams **36** will be N+1, where N is the number of micromirrors. Alternatively, the light beam **32** can travel through the substrate **22**, if the substrate is
15 transparent. For example, if the substrate **22** is made of silicon or glass, then the light beam **32** can travel through the substrate **22**.

Fig. 32 shows an alternative embodiment where a first reflection micromirror **20a** is tiltable. The light beam **32** is
20 initially parallel with the substrate **22**, and the tiltable micromirror **20a** provideds beam steering. In this embodiment, mechanical alignment between the light source **34** and the substrate **22** is not as critical. In fact, the light source **34**
25 can be located in any position relative to the substrate, provided that the light beam **32** is directed toward the first reflection micromirror **20a**.

Fig. 33 shows another embodiment of the present invention
30 having multiple tiltable micromirrors **20**. In the specific implementation of **Fig. 33**, alternate micromirrors are tilted so that the light beam **32** hits every second micromirror. This results in fewer emergent beams. Alternatively, the micromirrors can be tilted to hit every third or fourth

micromirror. In this way, the number and spacing of emergent beams **36** can be adjusted dynamically.

Fig. 34 shows another embodiment of the present invention
5 where the reflector **26** is not parallel with the array of micromirrors **20**. In this embodiment, the micromirrors **20** are tilted so that the light beam **32** does not 'walk off' the micromirrors as it travels. The tilt of the micromirrors **20** maintains a consistent spacing between adjacent emergent beams
10 **36**. The angle of the reflector 26 can be in the range of ±15 degrees or ±30 degrees. It is noted that the reflector **26** can be angled the opposite direction, i.e. so that the light beam **32** travels from a narrow gap to a wide gap. It is also noted that the angled reflector **26** tends to increase the FSR of the
15 device (compared to a device having a spacing T equal to the smallest spacing in a device with an angled reflector). In fact, the reflector **26** can be angled to increase the FSR and thereby improve the device for applications requiring a high FSR.

20

It is preferred for the mirror **42** or micromirrors **20** to have as large a reflectivity as possible. Light not reflected by the mirror or micromirrors is lost from the system, which is not desirable. For some devices, however, reflectivity of the
25 mirror or micromirrors can be as low as 20%.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the
30 invention should be determined by the following claims and their legal equivalents.